## MISSION DESIGN

The primary goal of this study is to examine the feasibility of using the novel Advanced RPS-driven Stirling thermoacoustic system to enable extended science operations in the extremely hostile surface environment of Venus. The mission concept entails landing a rover onto the Venus surface, conducting science measurements in different areas on the surface, and returning the science data to Earth. The study focused on developing a rover design to satisfy the science goals with the capability to operate for 60 days. This mission life influences several design parameters, including Earth elevation angle and the maximum communications range to Earth. No specific odometry requirement was defined for this concept study due to the uncertain surface topography and the likelihood of very rugged terrain. The thermal control system and electrical power systems were tailored to use the TASHE for vehicle power as well as cooling.

The trajectory design is constrained by three factors: Earth visibility, Sun visibility, and a low atmospheric entry angle. Since this concept relies on direct-to-Earth communication, the Earth must be in view of the rover during entry and after landing. The Sun must also be in view in order to perform visual science and navigation imaging, as well as allowing the rover to have improved knowledge of the Earth's location for communication support. Lastly, the entry ballute design requires a very shallow entry angle of -5 degrees. A 2013 Earth-Venus-Venus trajectory was selected that satisfies these requirements using a Delta IV launch vehicle and a C3 of 13.31 $km^2/sec^2$. Extensive trajectory analysis was not performed and more optimized solutions are likely to be available. The launch vehicle was chosen for its large fairing. The 3410 kg launch capability onto this trajectory provides a generous mass margin.

Entry, descent and landing would utilize a large inflated ballute that would minimize both the entry heating and deceleration loads (Figure 1). The nominal 64-m diameter ballute is deployed at an altitude of 140 km and at a speed of 11 km/s. The peak heating would be a very low 3.3 $W/cm^2$ and the peak deceleration would be 34 g's. The ballute would be jettisoned at 94 km altitude where the rover would be released to drop slowly through the thick atmosphere and land on the surface 76 minutes later. The rover impact acceleration would be further reduced by a platform of crushable material. The entry mass of 1008 kg includes the ballute system, rover vehicle, and rover entry/landing pad. The rover vehicle mass is 646 kg and includes 30% contingency on all elements.

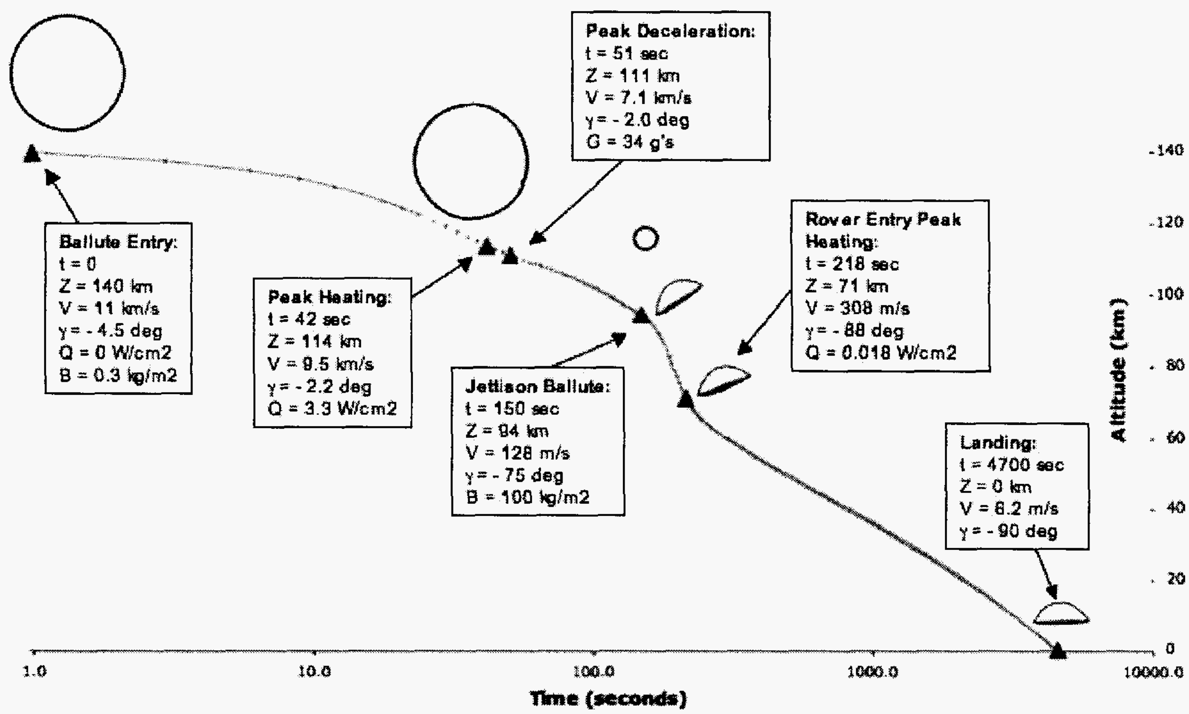


**FIGURE 1.** Venus rover entry, descent and landing sequence.

After a 20 month cruise duration, the rover would land just as the sun is rising, allowing 19 days of sunlit operations before the sun would set. The sun would rise again 78 Earth days later. Other trajectories are likely that would increase the initial period of sunlit operations with Earth visibility, however study scope limitations prevented this optimization. After landing, the rover would drive off its landing platform and begin in-situ operations. The nominal drive scenario for every 24 hours is to perform two 30-minute drives and four 165 minute data acquisition periods. During each day the data is returned to Earth using four 60-minute communication sessions. The remainder of the time is spent motionless while the batteries are recharged. Low power science operations might be performed during this period, such as meteorology measurements.

The rover's pressure vessel would be designed to minimize the parasitic heat associated with the surface area while providing sufficient wheel base for mobility. A cylindrical pressure vessel with spherical end-caps houses the electronics and instruments (Figure 2). The cylinder measures 1.5 meters long and 0.5 meters in diameter and would be constructed of 13.5 mm thick titanium.

Even though most of the rover systems include relatively mature technologies, several technology assumptions were made in developing this mission concept. The following technologies were assumed to be available at TRL 6 by 2009 to support a 2013 launch date: the TASHE system and high efficiency power alternator, high temperature secondary batteries, high temperature data and power cabling, high temperature S-Band antennas and RF co-axial cabling, high efficiency MLI, high temperature window ports and feed-throughs for the pressure vessel, 1-micron Sun sensor and optical fibers, and a high temperature mobility system.

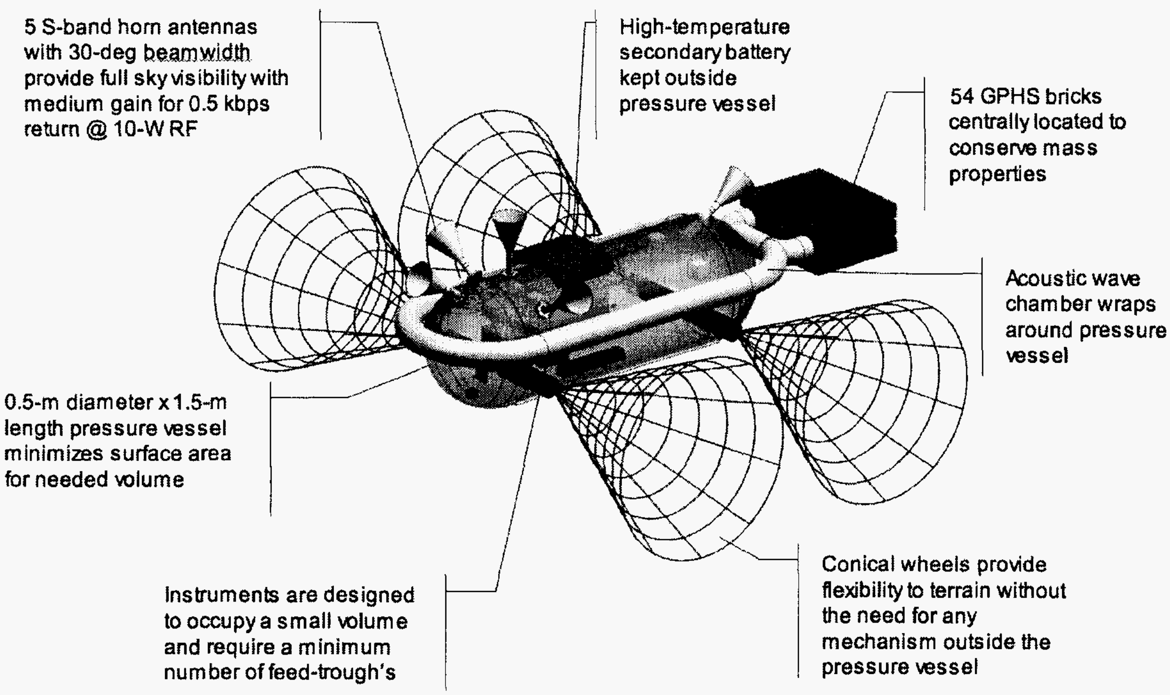


**FIGURE 2.** Conceptual Venus Rover Configuration.

## TASHE RPS SYSTEM

This rover mission concept uses RPS in a novel way to survive on the surface of Venus. An assembly of GPHS modules would be used as the heat source to drive a thermoacoustic Stirling engine yielding both electric power and critical refrigeration. The TASHE provides that novel capability. While working TASHE systems have operated in various laboratories at the kilowatt level, Northrup Grumman Space and Technology (NGST) and Los Alamos

National Laboratory have performed much work to scale the TASHE down to the 100-We power range (Tward, 2003)(Petach, 2004)(Backhaus, 2003).

The TASHE incorporates a Stirling heat engine that produces an acoustic pressure wave to drive a piston in a linear alternator which produces electricity (Tward, 2003). The thermoacoustic driver employs no moving parts to convert high-temperature heat into acoustic power. The TASHE is coupled with a vibrationally balanced flexure-bearing linear alternator to generate the electric power. NGST has demonstrated a system efficiency of 18% for a 50 We test unit and has developed a 100 We demonstration unit (Petach, 2004). Additionally, the thermoacoustic power drives a pulse tube cooler to provide critical cooling for this application. The 100 We TASHE unit in operation at NGST is shown in Figure 3.

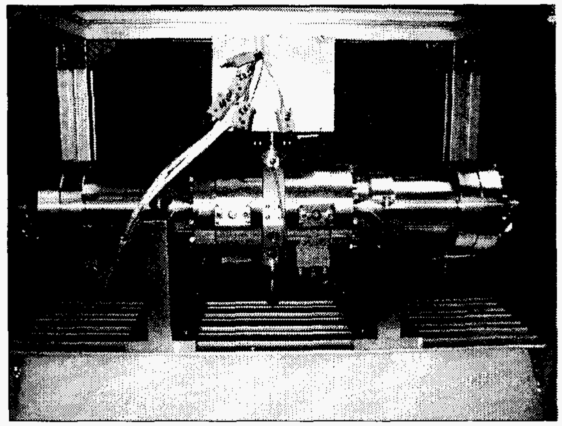

**FIGURE 3.** TASHE and Linear Alternator Operating at NGST.

The TASHE is composed of a closed loop flow path filled with high-pressure helium (Petach, 2004). The loop contains the regenerator, heat exchangers, and other ductwork necessary to force the helium gas in the regenerator to oscillate and execute a Stirling thermodynamic cycle when heat is applied. The GPHS modules (54) are placed in the gas loop and provide a 1200°C hot end heat source. In this design concept, the cold end heat exchanger is thermally coupled with the Venus atmosphere to provide a 500°C heat rejection temperature. To generate electric power, the oscillating gas flow impinges on the opposed pair of pistons in the linear alternator, which is derived from NGST's low-mass, flight-proven cryocooler compressors. The alternator's pistons are resonant with the thermoacoustic driver and generate electric power with their motion in the stators' magnetic fields.

The TASHE system would be mounted on the outside of the rover pressure vessel with the GPHS modules at the rear of the rover. Rover electronics would be housed in the front of the vessel to accommodate weight and balance requirements and gain distance from the ionizing radiation of the GPHS modules. The GPHS modules would be packaged in an insulated housing with an integrated channel network for transferring heat from the GPHS modules to the helium gas. Sized for the 120 Hz resonant frequency, the resonator tube is 3.3 m long and would be wrapped around the rover's exterior.

## SCIENCE INSTRUMENTS

A pressure vessel rover design presents challenges for science instrument selection and design. Optical systems must collect all imaging through small ports (there can be no external mast for a conventional panoramic camera). The navigation camera fields of view may be limited by these ports. Atmospheric sampling is proposed using a tiny inlet port that uses the high ambient pressure to ingest small samples into several collection containers. A mechanism would then move that sample away for analysis, while a new collection chamber is positioned for receiving another sample. This would allow the rover to take many atmospheric samples over the mission. Surface and atmospheric composition analyses would be performed with the Raman spectrometer and neutral mass spectrometer (NMS), respectively. The Raman spectrometer and X-ray fluorescence (XRF) instruments perform remote analysis of the outside surface materials through viewports while keeping the instruments inside the rover's pressure vessel.

Four cameras would be used for navigation, hazard avoidance, and surface imaging. Forward and rear facing pairs provide stereo images each way using 240x240 pixel CCDs at 10 bits/pixel and 5:1 compression. The nominal operations scenario includes two 30-minute drives during each 24 hours of operation. Navigation stereo images are taken every 2 minutes during those drives. The 15 stereo image pairs from each drive require 3.46 Mbits of storage per drive and 6.9 Mbits per day.

The IR sun sensor is primarily an engineering instrument and would be used for crudely finding the Sun line for use in ephemeris and navigation calculations to estimate the rover's location and predict Earth's location for selecting the downlink antenna. The ground penetrating radar (GPR) would take measurements during drive sequences to resolve subsurface layering. These measurements are also performed when the rover stops. The GPR data rate is 65 kbps and each brief measurement collects approximately 65 kbits. The meteorology station would measure atmospheric pressure, temperature, and wind speed. This instrument requires custom sensors designed to survive the high temperature and pressure environment.

## DATA HANDLING & COMMUNICATIONS

The avionics equipment would provide central processing functions as well as data storage, power distribution, and mobility controller electronics, along with interfaces for the instruments, communication, and navigation equipment. Processing is performed with a 3U format RAD750 processor board that supports speeds as high as 240 MIPS. Data storage is provided by 2 Gbits of solid-state non-volatile memory. Temperatures inside the pressure vessel would be less than 50°C, allowing the internal electronics to use Class-B components.

During a nominal 30-minute drive sequence, the rover would stop 15 times for taking navigation images and for taking GPR data. The navigation cameras generate 230 kbits of compressed image data for each stereo image pair. This yields approximately 3.46 Mbits of compressed images for a 30-minute drive. If GPR data is taken at each stop, then each 30-minute drive yields 975 kbits of GPR data, bringing the total data volume for a drive to about 4.5 Mbits. The compositional science instruments operate during periods when the rover is stationary. These data collection periods are estimated to generate about 720 kbits of data each.

Direct-to-Earth communication is provided by a dual-frequency telecommunication system using X-Band for commanding and cruise operations, and S-Band for downlink from the Venus surface. Using S-Band on the surface minimizes the RF and DC power requirements for downlink. Atmospheric attenuation at X-Band would be approximately 10 dB, while at S-Band it is only about 1 dB. The DSN 70-meter stations will still provide S-Band service for a 2013 - 2015 mission timeframe, however, the planned DSN 12-meter arrays would not support S-Band in the future.

A key design driver for this system is to avoid exposing any moving parts to the Venus atmosphere. This prevents using a gimbaled high gain antenna. Five fixed medium gain antennas (MGAs) are mounted to the upper side of the rover. For communication, one of these MGAs is selected by on-board sequences to maximize performance based on the rover's knowledge of Earth's location in the sky. The dual string design would use 10 W RF S-Band SSPAs to achieve 500 bps downlink at the maximum Earth range of 0.6 AU with a 4 dB link margin. Commanding is performed using X-Band and a low gain antenna on the rover's upper side. Uplink performance when using a 70 m DSN station is estimated to be 31 bps at 0.6 AU with 8 dB margin. The maximum Earth range of 0.6 AU occurs at the date of landing and drops below 0.6 AU for more than 100 days. Technology development is required to produce the RF feedthroughs that connect the amplifiers with the MGAs on the outside of the pressure vessel. These would effectively be solid RF transparent waveguides that seal small ports in the pressure vessel wall.

The nominal roving scenario includes four 60 minute communication sessions every 24 hours. This allows a total of 6.9 Mbits of data to be returned to Earth during each day of roving. Each stereo image pair requires approximately 8 minutes to relay to Earth. A nominal 30-minute drive includes a maximum of 15 GPR data sets and 15 stereo image pairs which dominate the total data volume. The total science data collected during a 30-minute drive is approximately 4.5 Mbits. Approximately 149 minutes is required to transmit this data to Earth.

## THERMAL CONTROL

Thermal control issues are highlighted in this mission due to the very hot surface temperatures (~460°C) and high pressures (~90 bars). The thermal control system must reject the large parasitic heat loads from the pressure vessel hull and from all its penetrations, totaling 300 Wt (Table 1). In addition, it must manage the thermal environment in the vacuum interior of the pressure vessel where all electronics are housed. The vessel maintains a vacuum at $10^{-6}$

torr. A vacuum environment helps minimize thermal loads by eliminating any convective heat transfer from the vessel walls. Getter material is employed to help maintain this vacuum by absorbing outgassing products from the components inside the vessel. The interior of the vessel is lined with MLI fabricated with high temperature, gold-plated titanium using metal salt crystal separators. Component heat in the interior is managed by radiative and conductive exchange with the cooler.

**TABLE 1.** Estimated Parasitic Heat Loads.

| Heat Source | Description | Thermal Load (Wt) |
|---|---|---|
| Pressure Vessel | Venus atmosphere adds 42.3 Wt/m2 over the surface area (3.14 m2) | 133 |
| Drive Motors | 32.5 Wt each x 4 motors | 130 |
| Optical Penetrations | 6 holes @ 0.5 cm and 0.5 Wt each | 3 |
| NMS Instrument | Atmospheric sampling assembly | 2 |
| Cable Penetrations | 8 feed-throughs (Manganin wire) @ 0.25 Wt each | 2 |
| RF Wave Guide | 5 wave guide conduits @ 6 Wt each | 30 |
| | | **Total: 300 Wt** |

The thermal control system relies on a pulse tube cooler that is integrated with the TASHE system to keep the rover's electronics below 50°C. Approximately 3 kW PV power is provided to the cooler for addressing the 300 Wt of parasitic heat loads. For this study, the cooler efficiency was estimated at 14 percent. A pumped capillary loop system is employed within the rover to move heat from the warm electronics to the cold heat exchanger.

The large number of GPHS modules generates over 13 kWt of heat that is transferred using passive high-temperature heat pipes to small carbon-carbon radiator panels. Approximately 4 $m^2$ of radiator surface area is required to radiate this heat to the Venus atmosphere. These radiators could be mounted on the outside of the pressure vessel or outboard of the GPHS module assembly.

## MOBILITY

Four large conical wheels would provide mobility for the rover. The wheel design is similar to those employed by Lavochkin's Marsokhod rover designs (The Planetary Society, 2005). An open design conical wire frame minimizes mass and allows elastic motion for shock absorption. Each wheel is driven by an independent electric motor that it designed to operate in a high temperature and pressure environment. The motors are mounted inside the rover pressure vessel and are isolated from the atmospheric pressure using labyrinth seals (Figure 4). The wheels are non-articulated and steering is achieved by skid-steering.

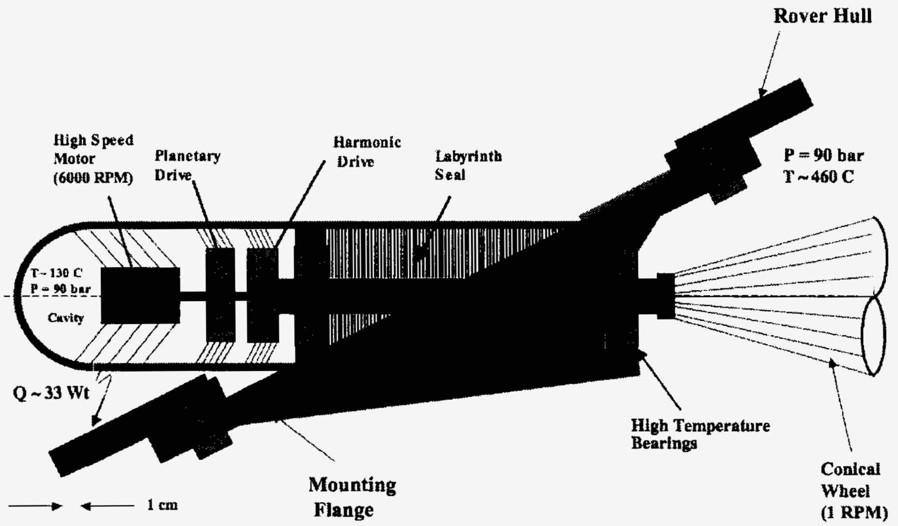


**FIGURE 4.** Venus Rover Drive Train Concept.

Rover control would be performed with preprogrammed sequences sent from Earth. The rugged terrain of some Venus regions may result in slow progress and very low odometry. This situation is somewhat mitigated by the rover's power and thermal control systems not being severely life limited as previous Venus missions have been. The current design concept would have limited rover operations during periods when the Earth is not in view or when the Sun has set. Without Earth contact, rover movement sequences cannot be sent to the rover and science data cannot be returned. Also, rover travel is impaired by darkness without any rover-based illumination source to assist in navigation imaging.

Mobility consumes the most power and generates the most internal heat in comparison to all other surface modes. To manage the heat load, roving is limited to two half-hour drives during a 24 hour period. Using the peak wheel speed of 1 rpm, the rover travels a maximum of 2.5-m per minute (assuming contact on the rim of the conical wheels). This results in a maximum range of 150-m per day from two 30 minutes drives. This maximum odometry does not include wheel slipping from traction loss and from skid steering, which is likely to occur. Also, the conical wheels will not always make contact with the surface at their greatest diameter.

Drive sequences would be planned on a daily basis and uploaded to the rover from Earth. To minimize the power and heat load, the rover would employ limited semi-autonomous control when driving, using its stereo navigation images to avoid obstacles or stop. This reduces the number of images that must be transmitted to Earth for controllers, significantly reducing the power and thermal loads.

## POWER

In this design, electric power is produced by the TASHE linear alternator during all mission phases. The alternator's steady 80 We (BOM) is supplemented by high-temperature secondary batteries to accommodate the high load power modes. Five significant power modes were defined in order to size the electric power subsystem for surface operations: *Roving, Telecom, Science, Recharge,* and *Wake* with total load values of 260.5, 123.4, 83.4, 39.4, 64.9 and 46.5 We respectively. The power and energy profile for a nominal day of roving is shown in Figure 5 including two 30-minute drive sequences, four 60-minute communications sessions, and four data collection periods.

A 10-Ahr $Na\text{-}NiCl_2$ "Zebra" battery was selected over Na-S and $LiAl\text{-}FeS_2$ batteries. While all of these batteries are designed for high-temperatures, the $Na\text{-}NiCl_2$ provides a high specific energy (approximately 110 Whr/kg) with a high technology readiness level. The battery is mounted on the top surface of the rover (colored blue in Figure 2). Additional packaging development would be required for this application.

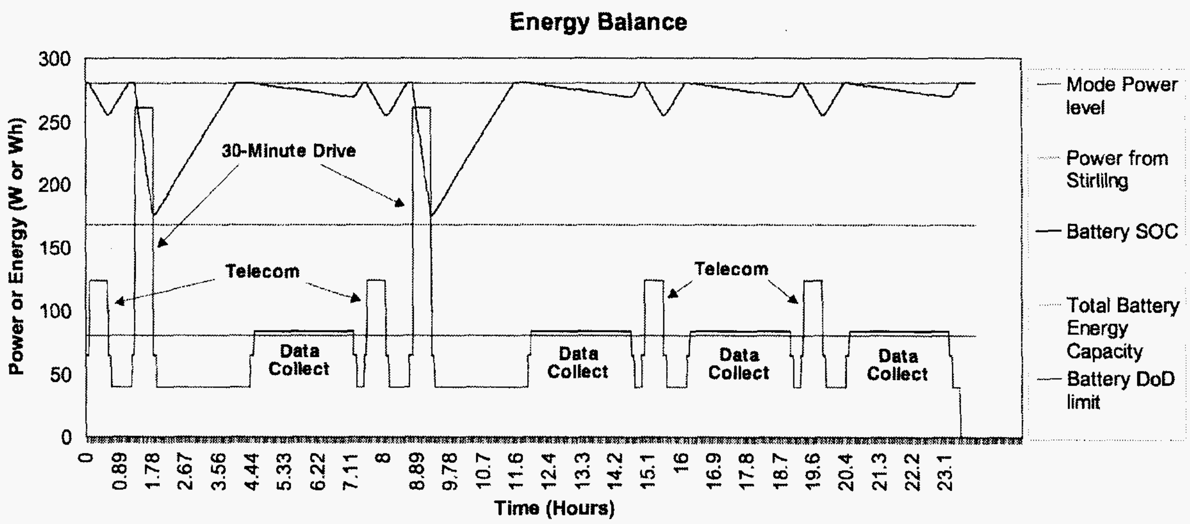


**FIGURE 5.** Power and Energy Profile for Nominal Daily Operations.

## SUMMARY

This Venus rover concept study illustrates the feasibility of using an advanced RPS-driven Stirling thermoacoustic heat engine to enable a mobile science platform on the surface of Venus with an operational lifetime far surpassing previous missions. The extreme heat and pressure of the surface atmosphere drive the rover design and configuration, as well as science instrument selection. Minimizing parasitic heat sources drives the design to have the smallest possible surface area, using a vacuum pressure vessel for electronics, and minimizing the number of penetrations through the pressure vessel. This is necessary to reduce the cooling load and thereby reduce the required number of GPHS modules. A stationary lander would not have any wheels and so would certainly benefit from fewer penetrations and a minimal surface area. However, mobility adds tremendous value to the science return for any Venus surface mission.

A nominal operational scenario was developed to balance the power demands from the drive and navigation systems, science instruments, and communications. High temperature batteries are mounted on the exterior of the rover and supplement the steady 80 We provided by the TASHE. Without adding an orbiter for communications relay, downlink direct to Earth is significantly aided by using S-Band. Static medium gain antennas are also mounted on the rover's exterior to provide downlink communication direct to Earth. Commanding is performed using X-Band, while downlink uses S-Band to minimize the DC power requirements. Atmospheric attenuation at X-Band is roughly 10 dB, while at S-Band it is only about 1 dB. Several technical challenges remain unaddressed, including the mobility system design and performance details, the possibility of driving in darkness based on navigation autonomy or illumination for navigation imagery, the design of the required pressure vessel pass-throughs, and the design for GPHS heat rejection during cruise and descent phases.

This point design illustrates the concept of using a novel RPS-based power and cooling system for a Venus rover mission while highlighting several key design factors that are applicable to other Venus surface missions. The TASHE system may enable operations on the surface of Venus for much longer than any previous actual or conceptual mission. Thermal control requirements drive any long-lived surface systems to smaller sizes, lower power use, and limited exposure to the atmosphere. Tremendous science value could be achieved with this novel RPS approach using the same number of GPHS modules as the currently active Cassini orbiter mission to Saturn.


## ACKNOWLEDGEMENTS

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## REFERENCES


Backhaus, S., "Initial Tests of a Thermoacoustic Space Power Engine," CP654, *Space Technology and Applications International Forum (STAIF 2003)*, edited by M.S. El-Genk, 2003 American Institute of Physics, 2003.

National Research Council, Space Studies Board, "New Frontiers in the Solar System: An Integrated Exploration Strategy," The National Academies Press, 2003.

Petach, M., Tward, E., and Backhaus, S., "Design of a High Efficiency Power Source (HEPS) Based on Thermoacoustic Technology," Final Report, NASA Contract No. NAS3-01103, CDRL 3f, January 2004.

The Planetary Society, "TPS: Exploring Mars: Images of Mars Rovers," http://www.planetary.org/mars/images-rovers.html, accessed May 19, 2005.

Tward, E., Petach, M., and Backhaus, S., "Thermoacoustic Space Power Converter," CP654, *Space Technology and Applications International Forum (STAIF 2003)*, edited by M.S. El-Genk, 2003 American Institute of Physics, 2003.